The Performance of Differential VLBI Delay During Interplanetary Cruise

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Project Voyager radio metric data are used to evaluate the orbit determination abilities of several data strategies during spacecraft interplanetary cruise. Benchmark performance is established with an operational data strategy of conventional coherent Doppler, coherent range, and explicitly differenced range data from two intercontinental baselines to ameliorate the low declination singularity of the Doppler data. Employing a Voyager operations trajectory as a reference, the performance of the operational data strategy is compared to the performances of data strategies using differential VLBI delay data (spacecraft delay minus quasar delay) in combinations with the aforementioned conventional data types. The comparison of strategy performances indicates that high-accuracy cruise orbit determination can be achieved with a data strategy employing differential VLBI delay data, where the quantity of coherent radio metric data has been reduced by over 95% with a concurrent 90% reduction in the DSN time allocated to radio metric data acquisition.

I. Introduction

Interplanetary missions of the future will impose increasingly stringent requirements on navigational systems for precision, accuracy, and overall economy. Chief amongst the radio metric systems developed to meet these demands is NASA's Deep Space Network (DSN) operational Very Long Baseline Interferometry (VLBI) system. A primary product of this system is the differential VLBI (DVLBI) delay data type, which is used in spacecraft orbit determination.

DVLBI delay offers performance that is currently unexcelled by any other radio metric data type in the determination of spacecraft angular position. (Data precision has been demonstrated at 70 nanoradians – approximately 10.5 km/AU, where 1.0 AU $\approx 149.6 \times 10^6$km.) An (implicit) accuracy of 50 nanoradians is anticipated by 1986 in support of Project Galileo. An extensive discussion of the data type and the associated VLBI system accuracies and attributes is provided by Border et. al. (Ref. 1).

The applicability of DVLBI delay to differental navigational situations has been a topic of great interest (Refs. 1 through 9). This article serves to solidify knowledge in this area by validating the significant contributions that DVLBI delay can make to spacecraft orbit determination during interplanetary cruise. Results are given that demonstrate that the addition of DVLBI delay to a cruise data strategy simplifies and economizes the determination of spacecraft state with retained or enhanced precision and accuracy.

The main text of this article begins with a discussion of the salient facts concerning the Voyager 2 Jupiter-to-Saturn cruise geometry. This discussion is followed by a description of the radio metric data and spacecraft tracking strategies used in the study. Then the study's assumptions and data filter structure are detailed. Thereafter, an assessment is made of the abilities of the competing data strategies to determine spacecraft state. This assessment is followed by a summary and presentation of conclusions.

II. Geometry

A segment of Voyager 2's 1981 Jupiter-to-Saturn cruise is employed for the study. Radio metric data coverage is from March 26th, the trajectory's epoch, to June 13th.

Voyager 2 maintained an absolute declination (DEC) of less than 1.4 degrees during the time of data coverage with a right ascension (RA) of approximately 183 degrees. A low DEC environment greatly reduces the spacecraft DEC sensitivity of coherent Doppler data, which are the traditional mainstay of radio metric tracking.

The sun-earth-spacecraft angle was greater than 100 degrees during the time of data coverage. A large angular separation between the sun and the spacecraft minimizes the dispersive effect that space plasma has on radio metric data.

III. Data Arc and Data Strategies

The investigated tracking data strategies are developed from eleven weeks of Voyager Navigation S-band radio metric data consisting of three coherent data types (Doppler, range, and differenced range) and DVLBI delay data acquired in a ground-station receive-only spacecraft tracking mode. Data from Deep Space Stations where the spacecraft's elevation angles are less than fifteen degrees are not used in the study. All radio metric data are calibrated with operationally employed seasonal models to account for radio signal delay due to the troposphere, and models developed from Faraday rotation data to account for signal delay due to the ionosphere.

Four tracks of Doppler data, each containing one range point, are included in each week of data. These data directly measure the spacecraft's line-of-sight velocity and distance, and, over a period of weeks, the combination of Doppler and range data determine spacecraft angular velocities. Hamilton and Melbourne (Ref. 10) have shown that each track of Doppler indirectly determines the spacecraft's RA and DEC. However, the accuracy of the DEC determination deteriorates rapidly as the spacecraft's DEC approaches zero.

Differenced range data measure spacecraft angular position and provide a means for amelioration of the low DEC singularity of Doppler data (Refs. 2, 11, and 12). This differenced data type is obtained by explicitly differencing two range points from two Deep Space Stations that define a "baseline." The Deep Space Station combination of Goldstone-Madrid (G-M) defines an east-west baseline; Goldstone-Canberra (G-C) defines a north-south baseline. (Data from the G-C baseline measure spacecraft DEC, while data from the G-M baseline measure spacecraft RA.) This differencing of range points reduces sensitivity to errors that are common to baseline stations, e.g., unmodeled spacecraft accelerations. Measurement accuracy is limited by errors that are not common to both stations such as station location errors, transmission media errors, and station instrumental effects.

The study data arc includes twenty G-M differenced range measurements and sixteen G-C differenced range measurements. Due to geometry constraints and coherency requirements, range points differenced in this study are offset in time from eleven minutes to over three hours. The resulting differenced range points are clustered at the beginning, middle, and end of the data arc.

Navigational DVLBI delay is a data type developed by differencing the VLBI delay measurements from a spacecraft and an angularly nearby natural radio source (typically a quasar), where each delay is determined as differential range obtained from simultaneous observation of each radio source by two widely separated Deep Space Stations. The result is a data type that measures the angular offset of the spacecraft from a known position in the sky (the quasar's angular position), whereas differenced range measures the spacecraft's total angular position in the sky. During the time frame of the study, the angular separation between Voyager 2 and the reference quasar (3C 273) varied between zero and three degrees. For the study, DVLBI delay data are included at the rate of one point from each of the G-M and G-C baselines per week.

For DVLBI delay data, the simultaneous observation of a radio source by two stations and the subsequent differencing over a baseline as well as the differencing between sources that are angularly close results in a data type that is highly self-calibrating. (The double differencing greatly reduces the effects of station common errors as well as the effects of errors that are common to each delay.) Inclusion of the quasar delay in the differencing process introduces an error in the DVLBI delay due to imperfect knowledge of the quasar's location (as determined from radio interferometry) with respect to the optically determined planetary ephemerides. This error is referred to as a "frame tie" error.

In a previous analysis of these data (Ref. 2), biases between differenced range and DVLBI delay were observed (-8 m on the G-C baseline and -4 m on the G-M baseline). Substantial contributions to the magnitudes of these biases can be credited to a frame tie error. In the current study, G-C and G-M biases have been reduced to -1.19 m and -0.85 m, respectively. The reductions in the biases are achieved by the determination of quasar positions with respect to Voyager models and values for Deep Space Station locations, earth orientation parameters, precession, and nutation (Border, J.S., and Sovers, O.J., "Radio Source Position Catalog for Delta DOR," Tracking Systems and Applications Section internal document, October 6, 1982).

The frame tie error is expected to be limited to 100 nanoradians in the near future. For the purpose of future applicability, a 1-sigma (one standard deviation) uncertainty or 100 nanoradians is assumed for each component of quasar position in this study.

The data strategies examined are outlined in Table 1. The nominal operational data mix is reflected in strategy A. This strategy involves least squares fitting to all available tracks of Doppler data where these data have been augmented by occasional range points, and differenced range data (particularly from the G-C baseline for DEC sensitivity) under low DEC conditions. This approach typically results in a data set that contains hundreds if not thousands of points. In strategy B, all of the available Doppler, range, and DVLBI delay data are combined. The total number of points in this strategy is comparable to the total number in strategy A. In strategy C, the DVLBI data are combined with one Doppler point and one range point per week. Strategy D combines one Doppler point and one range point per week with one DVLBI delay point every two weeks from each baseline. Strategy E combines the delay data with one range point per week.

Examination of Fig. 1 reveals that strategies C, D, and E, when compared to strategy A, achieved reductions in data volume greater than 95% and reductions in station tracking time that approach 90%.

IV. Filter Structure and Assumptions

Covariances for each data strategy are generated and propagated by a (least squares) Square Root Information Consider Filter (Ref. 13). These covariances are derived from the estimation of the spacecraft's state, impulsive maneuvers, and nongravitational accelerations due to gas leaks in the spacecraft's attitude control system. These accelerations are treated as biases and as white process noise in a four-day batch structure. The effects of errors in quasar RA and DEC are considered as are the effects of errors in station longitudes, distances off the earth spin axis, and distances above the equatorial plane. Nominal a priori sigmas and assumed correlations between station coordinates are listed in Table 2.

For each data strategy, 1-sigma a priori uncertainties for the data types are 1 mm/s for Doppler (for a 60-s count time), 10 km for range, 5 m for differenced range, and 2 m for DVLBI delay. A relatively large uncertainty is assumed for range data to allow for the range's noisier quality and vulnerability to unknown accelerations in the spacecraft's line-of-sight direction with respect to DSN stations (Ref. 14).

V. Performance of Data Strategies

The nominal spacecraft trajectory employed in this study is developed from Voyager force and ephemeris models, and Doppler, range, and differenced range data that were operationally acquired prior to the start of the study data arc. Each data strategy is used to correct the initial spacecraft state and to derive associated error covariances. These covariances and corrected states are examined in a plane-of-sky frame at the end of the data arc.

The magnitudes of postfit data residuals provide indications of how effective data strategies are in eliminating systematic signatures in the data. Figure 2 displays the reductions in root-mean-square residual values realized for each data type in the respective strategies. It can be observed that strategies B, C, and D, which involve DVLBI delay data, achieved reductions in data scatters varying from 40% for delay and differenced range data to 96% for range data. These reductions in scatters are very close to the reductions obtained with strategy A, which utilized only the coherent data types. Reductions in scatters obtained with strategy E, which relies on infrequent range points and DVLBI delay data, are less dramatic by only a factor or two. Thus, the DVLBI strategies are nearly as effective as the conventional strategy in removing signatures from the data.

As summarized in Table 3, the DVLBI strategies provide estimates of state that are in close agreement with the conventional state estimate at the end of the data arc. In particular, RA and DEC estimates differ by maximums of 36 km and 125 km (27 nanoradians and 92 nanoradians), respectively, at 9.035 AU.

Figures 3 and 4 show the geocentric plane-of-sky uncertainties at the end of the data arc. The effects that the considered parameters have on state uncertainty are shown in Figs. 5 through 10.

For conventional tracking, station longitudes and spin axis distances are the dominant error sources. It can be seen from

Figs. 5 and 6 that, for strategy A, 1-sigma errors in these station parameters contribute uncertainties of nearly 600 km to RA and 200 km to DEC compared to total uncertainties of roughly 650 km and 420 km, respectively (Figs. 3 and 4).

In the DVLBI strategies, total uncertainties in RA and DEC are under 230 km and 375 km, respectively. Inspections of Figs. 5 and 6 reveal that the DVLBI strategies reduce the effects of errors in longitudes and spin axis distances by more than an order of magnitude. In particular, for strategies C, D, and E, the components of quasar position are the dominant error sources in the determination of spacecraft RA and DEC. A 1-sigma error in quasar RA contributes 125 km to uncertainty in spacecraft RA. Similarly, a 1-sigma error in quasar DEC contributes 125 km to uncertainty in spacecraft DEC. Note that Fig. 4 shows that the DVLBI strategies also reduce the uncertainties in the rates for RA and DEC by 10% to 15%.

In the DVLBI strategies, the effects of errors in the considered parameters are subkilometer for radial distance (Fig. 7), and less than 0.7 mm/s for radial velocity (Fig. 10). The uncertainties in these components of state increase in strategies C and E, for which the quantities of Doppler and range data are reduced. The increase in these uncertainties is to be expected since Doppler and range data are strongest in determining the radial components of state.

Comparable uncertainties in the radial components are obtained with the strategies that include Doppler data. Uncertainties in the position component are approximately 1.7 km for strategies A and B, and 3.2 km for strategies C and D. The position uncertainty increases to 13 km in strategy E, which does not include Doppler. Radial velocity uncertainty is 4.5 mm/s for strategy A, and less than 2 mm/s for strategies B, C, and D. The lower uncertainty in radial velocity for DVLBI strategies B, C, and D results primarily from the decoupling of radial velocity from station longitudes. In strategy E, velocity uncertainty increases to 9 mm/s. This increase in uncertainty is due to the lack of a direct measure of radial velocity and the high correlation between radial velocity and a loosely determined radial component of position.

The performances of the above DVLBI strategies demonstrate that improved orbit determination accuracy can be achieved, with a concurrent reduction in the requirement for navigation and tracking system resources, if DVLBI delay data are added to a cruise tracking strategy.

VI. Summary and Conclusions

Results have been presented that are believed to be realistic indications of the cruise orbit determination enhancements achievable when DVLBI data are included in radio metric data strategies. These enhancements are reflected in the ability of DVLBI strategies to satisfy the increasing demands placed on navigation systems to develop methods for the determination of spacecraft state with greater economy without compromising state accuracy requirements.

DVLBI strategies were shown to provide estimates of spacecraft state that closely agree with the conventional state estimate and are generally less uncertain than the conventional state estimate. The most accurate estimates of state were obtained with the DVLBI strategies, which included infrequent coherent Doppler and range data. The high level of accuracy achieved with the DVLBI strategies is partially due to the relative immunity of DVLBI strategies to conditions and error sources that are significant accuracy constraints in conventional tracking. In DVLBI strategies, sensitivity to spacecraft declination is retained in low declination environments and quasar RA and DEC replace station-location parameters as dominant error sources, although at substantially lower levels. As the uncertainty in the tie between the planetary ephemeris frame and quasar reference frame decreases below 100 nanoradians (a level expected to be a achieved in the near future), the effects of errors in quasar RA and DEC will be diminished.

DVLBI strategies were shown to economize orbit determination. The maximum reduction in data volume exceeded 95% of the conventional benchmark, while the maximum reduction in station tracking time approached 90%. These savings imply reduced requirements for data management and processing resources.

The above contributions of high-level accuracy and economy cast DVLBI strategies as compelling alternatives to the conventional coherent data strategy for cruise orbit determination.

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Table 1. Data strategies

Data Type	A (Conventional)	B	C	D	E
Doppler	Four 5-h passes per week	Four 5-h passes per week	One observation per week	One observation per week	–
Range	Four observations per week	Four observations per week	One observation per week	One observation per week	One observation per week
Differenced Range	20 E-W observations 16 N-S observations	–	–	–	–
DVLBI	–	One E-W observation per week One N-S observation per week	One E-W observation per week One N-S observation per week	1/2 E-W observation per week 1/2 N-S observation per week	One E-W observation per week One N-S observation per week

Table 2. 1-sigma a priori uncertainties for estimated and considered parameters

Parameters	Uncertainties	Intercontinental station-pair correlations
Spacecraft position	10^6 km[a]	–
Spacecraft velocity	1 km/s[a]	–
Maneuvers	10^{-5} km/s[a]	–
Nongravitational accelerations	5×10^{-12} km/s^2[a]	–
Station spin axis distance	1.5 m	0.778
Station longitude	3×10^{-5} deg	0.955
Station equatorial height	15 m	0.998
Quasar position	100 nrad[a]	

[a]Each component.

Table 3. Maximum difference between the conventional estimate of state and the DVLBI estimates of state and the DVLBI estimates

Parameter	Position components, km	Velocity components, mm/s
RA	36	39
DEC	125	25
Radial	1	1

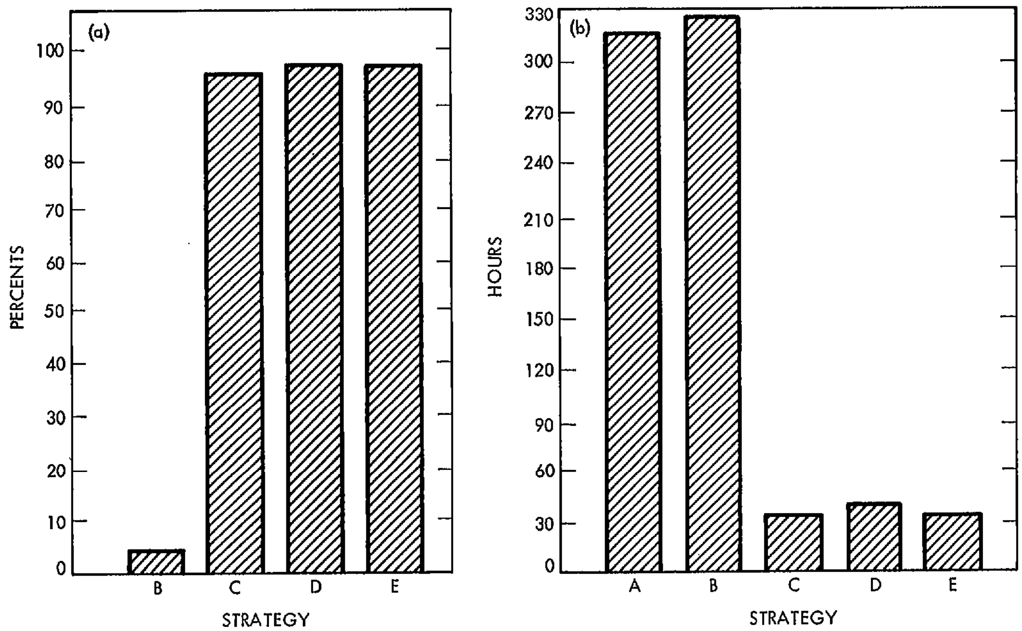

Fig. 1. Resource requirements: (a) reductions in the number of data points with respect to the strategy A; (b) station nominal tracking time requirements

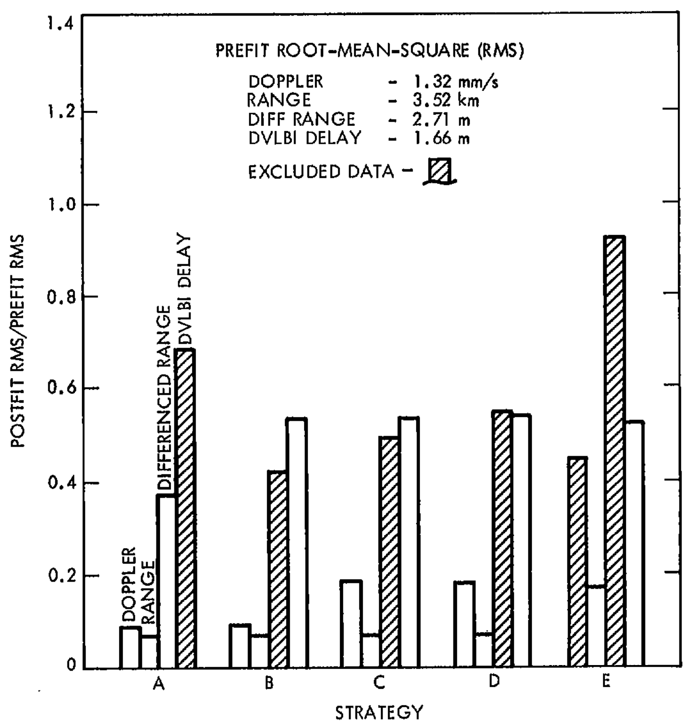

Fig. 2. Reductions in data scatters achieved with each data strategy

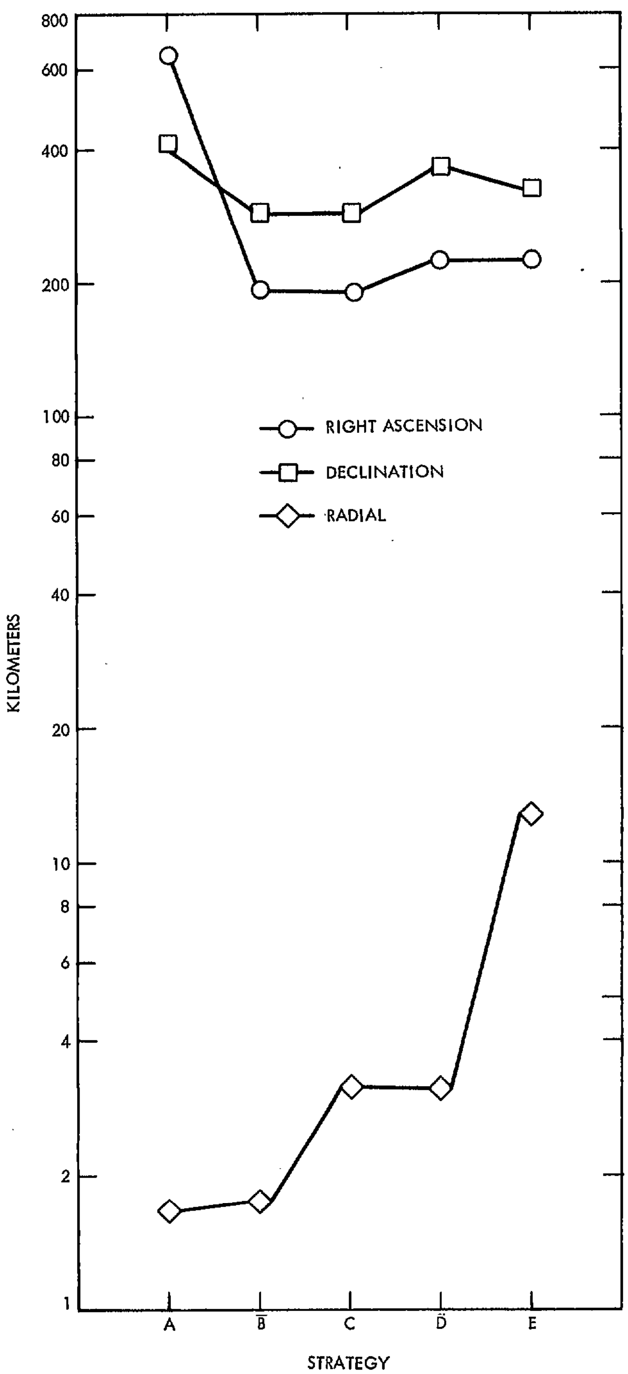

Fig. 3. 1-sigma spacecraft geocentric position component uncertainties at 9.035 AU

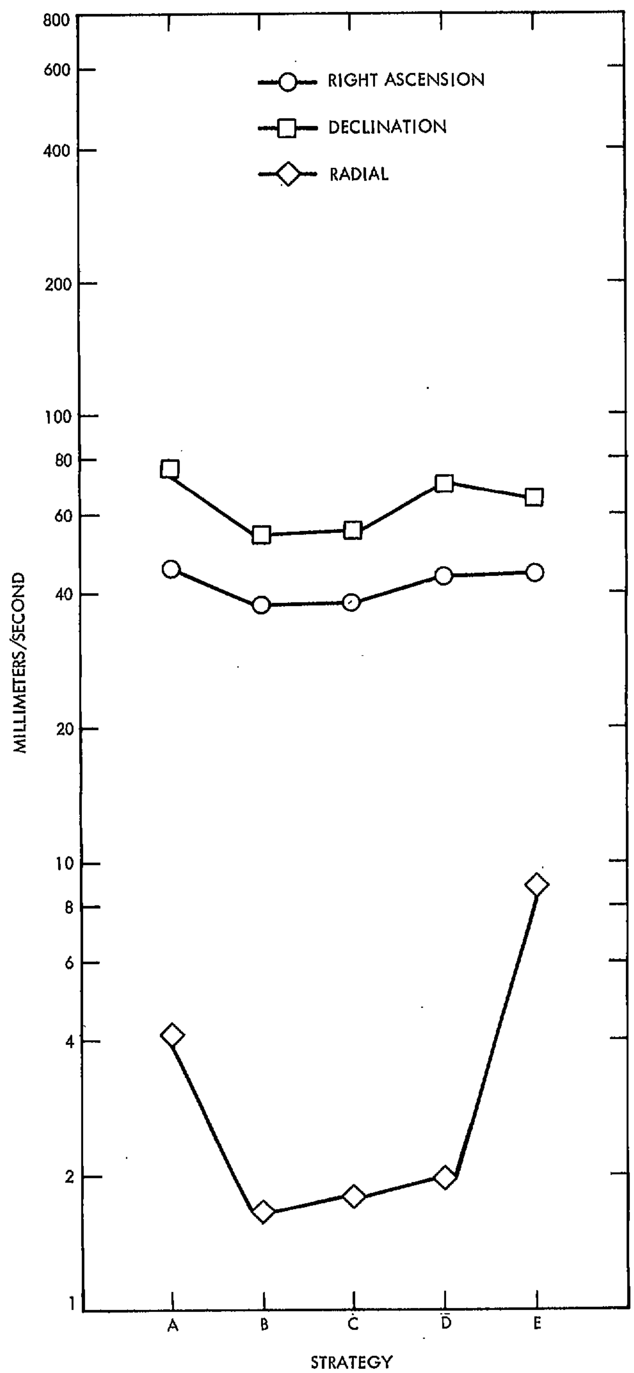

Fig. 4. 1-sigma spacecraft geocentric velocity component uncertainties at 9.035 AU

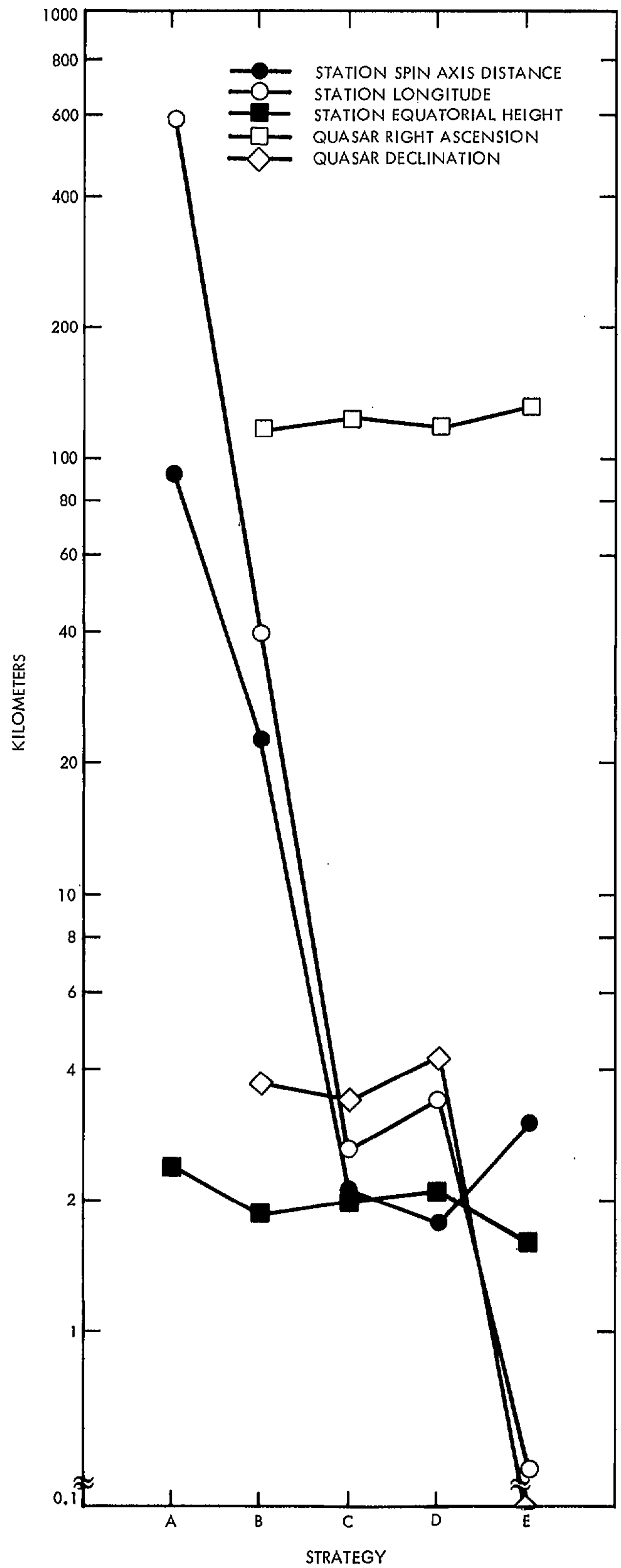

Fig. 5. Contributions of considered parameters to uncertainty in spacecraft geocentric right ascension at 9.035 AU

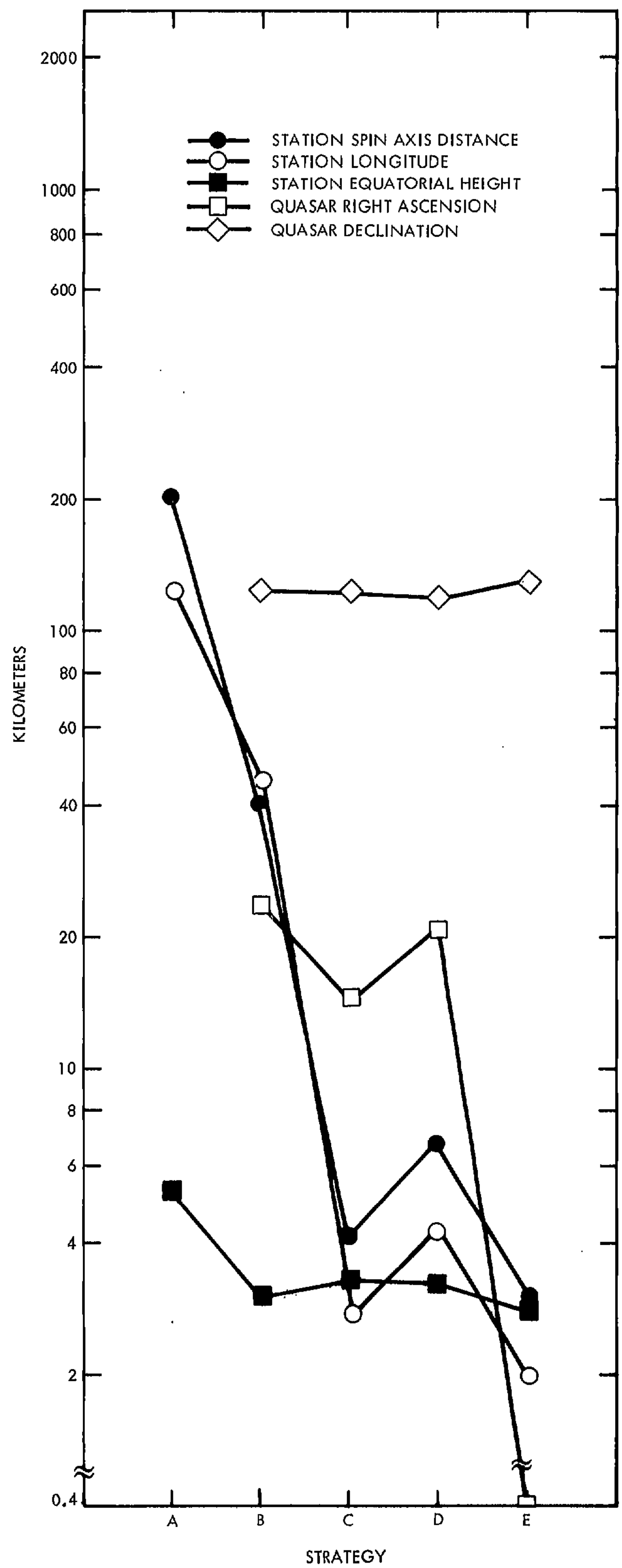

Fig. 6. Contributions of considered parameters to uncertainty in spacecraft geocentric declination at 9.035 AU

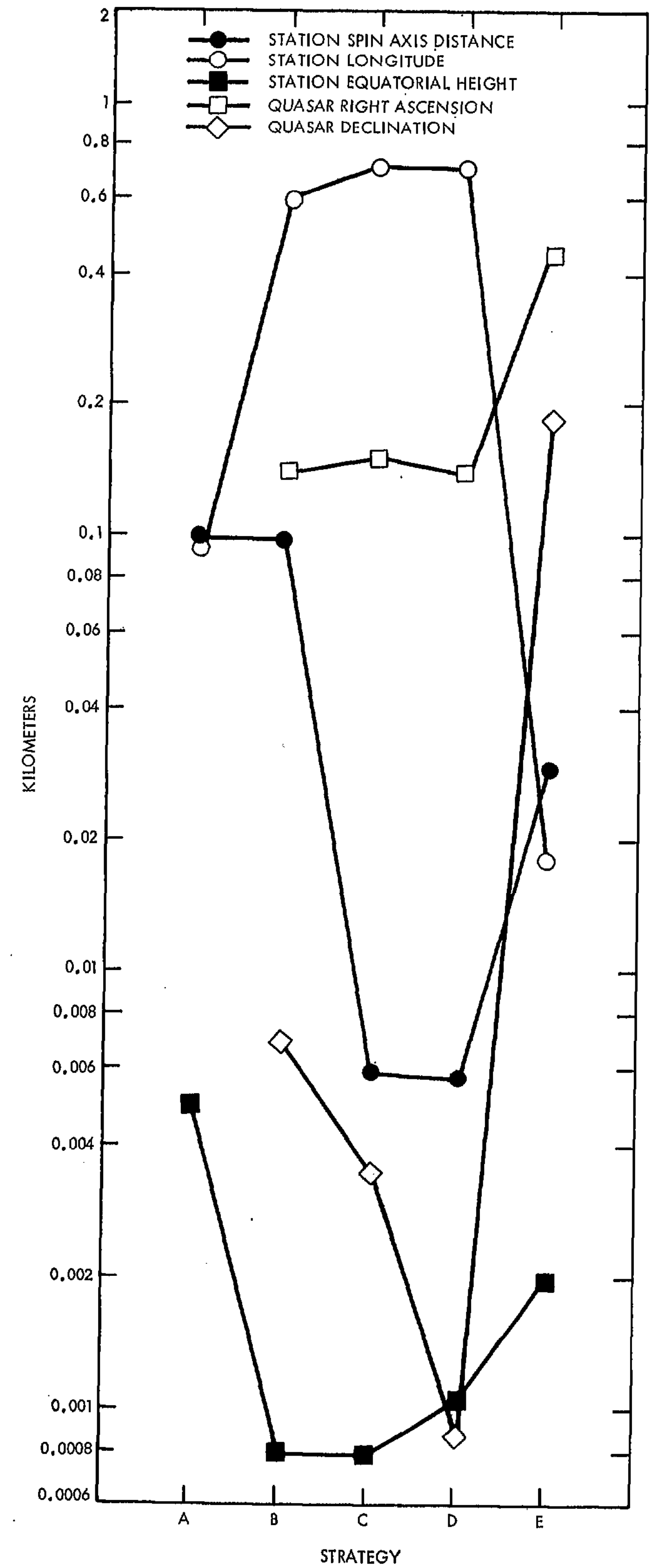

Fig. 7. Contributions of considered parameters to uncertainty in spacecraft geocentric radial distance at 9.035 AU

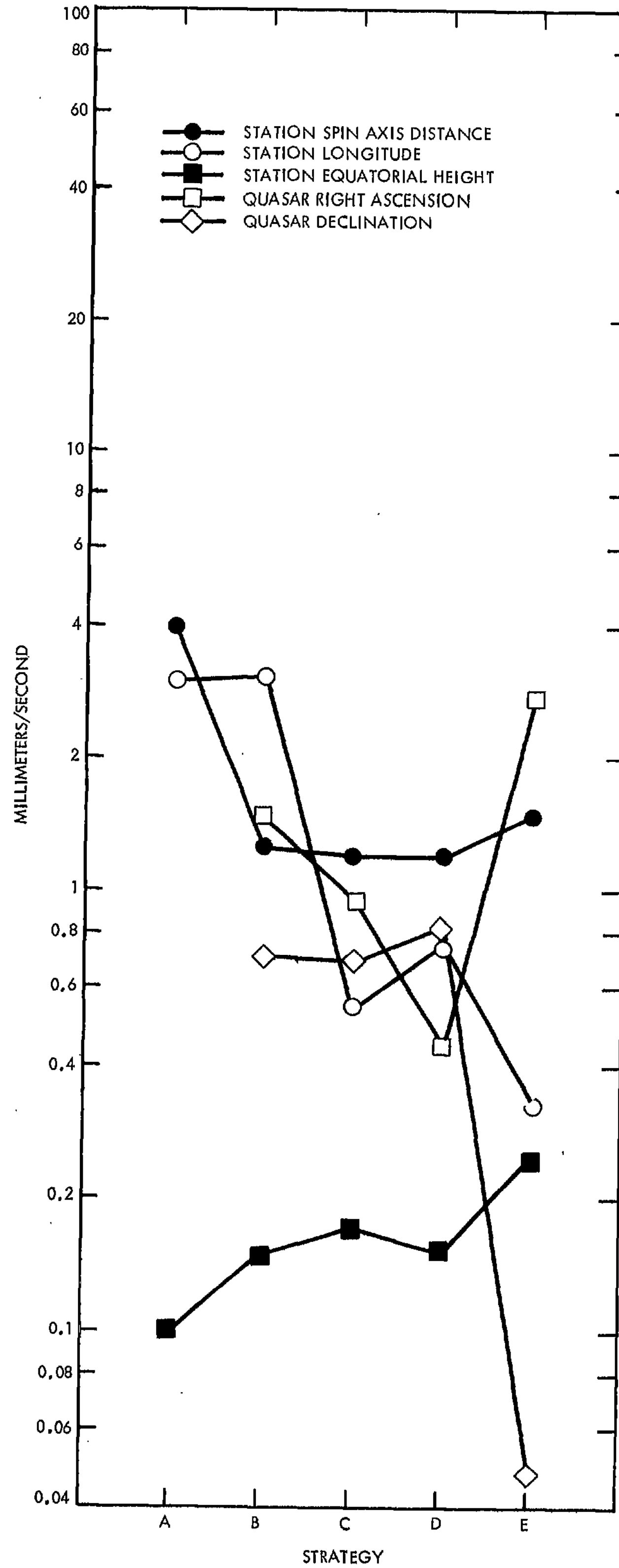

Fig. 8. Contributions of considered parameters to uncertainty in spacecraft geocentric right ascension rate at 9.035 AU

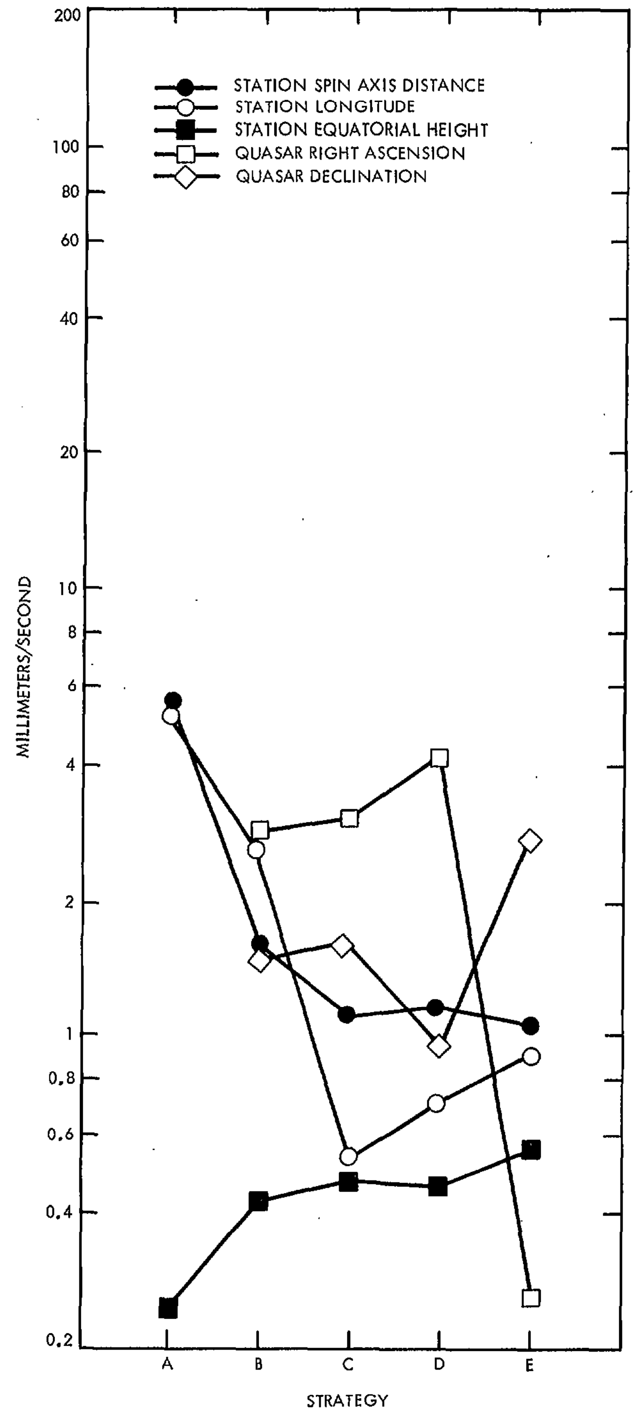

Fig. 9. Contributions of considered parameters to uncertainty in spacecraft geocentric declination rate at 9.035 AU

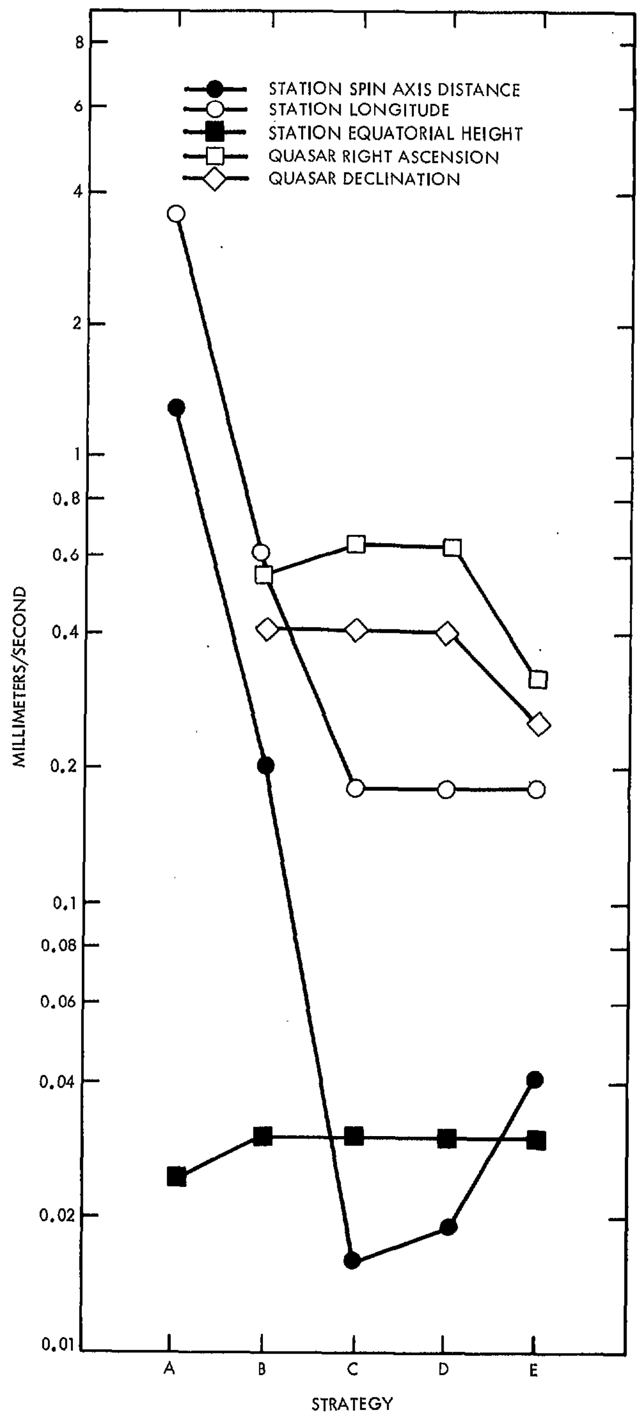

Fig. 10. Contributions of considered parameters to uncertainty in spacecraft geocentric radial velocity